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I, Susan ANTHONY BA, ACIS,

Director of RWS Group plc, of Europa House, Marsham Way, Gerrards Cross, Buckinghamshire, England declare;

1. That I am a citizen of the United Kingdom of Great Britain and Northern Ireland.
2. That the translator responsible for the attached translation is well acquainted with the German and English languages.
3. That the attached is, to the best of RWS Group plc knowledge and belief, a true translation into the English language of the specification in German filed with the application for a patent in the U.S.A. on  
under the number
4. That I believe that all statements made herein of my own knowledge are true and that all statements made on information and belief are true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the patent application in the United States of America or any patent issuing thereon.

A handwritten signature in black ink, appearing to read "S. Anthony BA".

For and on behalf of RWS Group plc

The 19th day of April 2004

Description

Method for producing a vertically emitting laser

5 The invention relates to a method for producing a vertically emitting laser, in particular a VCSEL laser (VCSEL: Vertical Cavity Surface Emitting Laser). VCSEL lasers emit light perpendicularly to the surface, so that lasers of this type are predestined for low-cost  
10 applications. On account of their geometrical form, however, VCSEL lasers tend to emit their light in transverse multimode fashion. However, multimodality leads to a mode noise, which is disturbing if data transmission at a high bit rate is to be effected.  
15 Moreover, transverse multimodality leads to increased coupling losses.

Prior art:

The document "Transverse Mode Selection in Large-Area Oxide-Confining Vertical-Cavity Surface-Emitting Lasers Using a Shallow Surface Relief" (H. Martinsson, J. Å. Vukusic, M. Grabherr, M. Michalzik, R. Jäger, K. J. Ebeling, A. Larsson; IEEE Photonics Technology Letters, Vol. 11, No. 12, December 1999, pages 1536-25 1538) describes a method for producing a VCSEL laser, in which a so-called "semiconductor relief" is produced on the surface of the VCSEL laser. The function of the semiconductor relief is to suppress higher modes of the light generated in the active zone of the laser and to  
30 leave only the fundamental mode of the light as far as possible uninfluenced. In essence, the functioning of the semiconductor relief is based on the fact that higher modes have a field distribution in the case of which the light is guided principally at the edge of  
35 the radiation lobe of the light. In contrast thereto, the fundamental mode has a radiation behavior in the case of which the light is situated principally in the inner region of the radiation lobe of the light. The semiconductor relief thus preferably suppresses higher

modes, so that principally or exclusively the fundamental mode of the VCSEL laser is coupled into optical components arranged downstream of the VCSEL laser.

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In the case of the VCSEL laser in accordance with the already cited document "Transverse Mode Selection in Large-Area Oxide-Confined Vertical-Cavity Surface-Emitting Lasers Using a Shallow Surface Relief", the 10 semiconductor relief is arranged on the top side of the VCSEL laser, that is to say above the upper mirror or mirror stack of the VCSEL laser. The semiconductor relief is thus separated from a current aperture of the VCSEL laser by the upper mirror layer of the laser. In 15 the case of the VCSEL laser shown in the document, the current aperture has an area size with a diameter of 15.5  $\mu\text{m}$ . In this case, the area size of the semiconductor relief is understood to be the area size of the inner raised region of the semiconductor relief. 20 The current aperture arranged below the upper mirror layer of the VCSEL laser has an area size (or a diameter) which is larger than the area size (or the diameter) of the semiconductor relief. In concrete terms, the diameter of the current aperture is 20  $\mu\text{m}$ .

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The document "Increased-area oxidized single-fundamental mode VCSEL with self-aligned shallow etched surface relief" (H. J. Unold, M. Grabherr, F. Eberhard, F. Mederer, R. Jäger, M. Riedl, K. J. Ebeling; 30 Electronics Letters, 5th August 1999, Vol. 35, No. 16) furthermore discloses a method for producing a laser, in which the semiconductor relief and the current aperture are produced in a self-aligning manner. This means that the current aperture is arranged in a 35 concentrically aligned manner relative to the semiconductor relief. The self-alignment is achieved by virtue of the fact that both the position of the semiconductor relief and the position of a mesa structure of the VCSEL laser are defined in the same

mask step. The mesa structure is produced in subsequent etching steps, the semiconductor relief inevitably remaining arranged centrally in the mesa structure. The area size of the current aperture is defined in the context of an oxidation step during which the sidewalls of the etched mesa structure are oxidized. This oxidation step effects lateral "oxidation into" the current aperture layer contained in the mesa structure. The semiconductor relief is separated from the current aperture by an upper mirror layer.

Object of the invention:

The invention is based on the object of specifying a method which makes it possible to produce VCSEL lasers with even better optical properties than heretofore.

Summary of the invention:

This object is achieved according to the invention by means of a method having the features in accordance with patent claim 1. Advantageous refinements of the method according to the invention are specified in subclaims.

Accordingly, the invention provides a laser production method in which a current aperture and a semiconductor relief are produced; the area size of the semiconductor relief and the area size of the current aperture are defined in the same production step.

An essential advantage of the method according to the invention is that it is always ensured that the area size of the semiconductor relief and the area size of the current aperture are in a fixed relationship with respect to one another, since both the semiconductor relief and the current aperture are defined in the same production step. By way of example, if production tolerances occur on account of fluctuations in the production conditions (e.g. production temperature, moisture fluctuations), then the area size of the

semiconductor relief will change under certain circumstances; however, since the semiconductor relief and the current aperture are defined in the same production step, the area size of the current aperture will also simultaneously be affected by the fluctuations in the production conditions, so that its size changes as well. As a result, the area size of the semiconductor relief and the area size of the current aperture will consequently change relatively "similarly", so that they will nevertheless have a size ratio with respect to one another that corresponds to the actually desired size ratio without production tolerances. The area size of the semiconductor relief and the area size of the current aperture thus comply with a predetermined size ratio "in a self-scaling manner"; a "self-scaling" does not occur in the case of the previously known method described in the introduction, because the definition of the semiconductor relief and the definition of the current aperture are effected in separate production steps.

A further essential advantage of the common production process for the semiconductor relief and the current aperture is that the yield in the production of the lasers is increased: it is because generally each current aperture diameter is matched only by a specific semiconductor relief diameter in order to obtain a single-mode radiation with a maximum optical output power at the output of the laser. The fixed scaling of the semiconductor relief and of the current aperture considerably increases the production yield and the process stability.

The area size of the semiconductor relief and the area size of the current aperture may be defined for example in an oxidation step; this procedure is advantageous in particular because current apertures are usually produced in an oxidation step. Consequently, in this refinement of the method, the size of the semiconductor

relief is defined during the oxidation of the current aperture.

During the production of the VCSEL laser, an oxidizable auxiliary layer for the definition of the area size of the semiconductor relief and an oxidizable current aperture layer for the definition of the current aperture are preferably subjected to the common oxidation step. In this case, the ratio between the oxidation rate of the oxidizable auxiliary layer and the oxidation rate of the current aperture layer defines the size ratio between the area size of the resulting semiconductor relief and the area size of the resulting current aperture. The oxidizable auxiliary layer and the current aperture layer may be for example layers made of AlGaAs material, the proportion of aluminum determining the oxidation rate: the higher the proportion of aluminum, the greater the oxidation rate.

During the production of the VCSEL laser, a mesa structure is preferably produced, which mesa structure encompasses or includes the oxidizable auxiliary layer and also the current aperture layer. The sidewalls of the mesa structure are subsequently oxidized, thereby also effecting oxidation "into" the oxidizable auxiliary layer and the current aperture layer within the mesa structure. The size ratio between the area size of the semiconductor relief and the area size of the current aperture is defined in this case.

In order to produce the VCSEL laser, it is possible, by way of example, firstly to arrange at least one semiconductor intermediate layer on the oxidizable current aperture layer of the VCSEL laser. The oxidizable auxiliary layer is subsequently arranged on the semiconductor intermediate layer. A covering layer is applied to the oxidizable auxiliary layer, for example by being grown epitaxially. The mesa structure is subsequently etched into the resulting layer stack,

and the sidewalls of the mesa structure are subjected to the oxidation step. The oxidizable current aperture layer and the oxidizable auxiliary layer are laterally oxidized simultaneously during this oxidation step.

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The VCSEL laser is completed particularly simply and thus advantageously by subsequently removing the oxidizable auxiliary layer in its oxidized regions, a region of the semiconductor intermediate layer being uncovered. The semiconductor intermediate layer is subsequently etched in the uncovered region down to a depth corresponding to the depth of the semiconductor relief to be produced. In addition, the covering layer and the non-oxidized regions of the oxidizable auxiliary layer are completely removed, thereby uncovering the semiconductor relief in the semiconductor intermediate layer. This then concludes the formation of the semiconductor relief.

20 Afterward, a mirror layer or a mirror layer stack comprising a plurality of mirror layers, which forms the upper mirror layer of the laser, is preferably deposited on the semiconductor relief. The semiconductor relief is thus arranged between the 25 mirror layer of the VCSEL laser and the current aperture of the VCSEL laser.

In contrast to the previously known methods mentioned in the introduction, the area size of the semiconductor relief is preferably made to be larger than the area size of the current aperture in order to achieve an optimum radiation behavior.

35 The upper mirror layer (or the upper mirror layers) deposited on the semiconductor relief may be for example layer stacks or layer pairs made of dielectric materials, preferably made of aluminum oxide and titanium oxide.

Furthermore, it is regarded as advantageous if an upper electrical contact of the VCSEL laser is arranged in a self-aligned manner relative to the current aperture and relative to the semiconductor relief, as a result of which a homogeneous current injection is achieved.

10 The upper electrical contact is preferably an intra-cavity contact, that is to say a contact which makes contact with a semiconductor layer of the VCSEL laser that is arranged below the upper mirror layer of the VCSEL laser.

15 The intra-cavity contact may be formed for example on the semiconductor intermediate layer already mentioned above.

20 The invention furthermore relates to a vertically emitting laser, in particular a VCSEL laser, with an as far as possible optimum radiation behavior.

25 The invention provides a laser, in particular a VCSEL laser, with a semiconductor relief for radiating undesirable modes, in which the semiconductor relief is arranged between an upper mirror layer of the laser and a current aperture of the laser.

30 Disturbing higher modes of the laser can be suppressed particularly simply and thus advantageously if the area size of the semiconductor relief is chosen to be larger than the area size of the current aperture. One advantage of the area ratio chosen in this way between the semiconductor relief and the current aperture consists in avoiding incomplete depletion of charge carriers below the semiconductor relief and - caused by 35 a slow diffusion process - impairment of the modulation behavior of the laser.

The mirror layer of the VCSEL laser preferably comprises layer stacks or layer pairs made of

dielectric materials, preferably made of aluminum oxide and titanium oxide.

As already mentioned in the introduction the VCSEL 5 laser may have an intra-cavity contact as the upper electrical contact; as an alternative or in addition, the second or "lower" electrical contact of the laser may also be an intra-cavity contact.

10 For elucidating the invention,

15 Figures 1-8 show a first exemplary embodiment of the method according to the invention and a laser according to the invention on the basis of diagrammatic illustrations,

20 Figures 9-16 show a second exemplary embodiment of the method according to the invention and a laser according to the invention on the basis of diagrammatic illustrations, and

25 Figures 17-23 show a third exemplary embodiment of the method according to the invention and a laser according to the invention.

In Figures 1 to 23, the same reference symbols are used for identical or comparable components.

30 Firstly, a first exemplary embodiment of the invention is explained in connection with Figures 1 to 8. Figure 1 shows a semiconductor layer stack 10 comprising a lower mirror layer stack 20 having a plurality of lower mirror layers, a lower weakly doped laser layer 30, an active (photon-generating) laser layer (laser zone) 40, a weakly doped upper laser layer 50, a current aperture layer 60, a semiconductor intermediate layer 70, an oxidizable auxiliary layer 75 and a covering layer 80.

The semiconductor layer stack 10 is arranged on a substrate 85.

5 A mask layer 100 is applied on the covering layer 80 of the semiconductor layer stack 10, which mask layer is patterned and will subsequently define a mesa structure. The mask layer 100 may be formed by a hard mask or a photoresist mask; a hard mask made of an oxide or made of a nitride, for example, is preferably 10 involved.

15 The semiconductor layer stack 10 illustrated in Figure 1 is subjected to an etching step, thereby forming the mesa structure 110 illustrated in Figure 2. It can be seen that the mask layer 100 is slightly undercut.

20 The sidewalls 115 of the mesa structure 110 are subsequently subjected to an oxidation step. Particularly the current aperture layer 60 and also the oxidizable auxiliary layer 75 oxidize in this case, since these two layers are particularly disposed to oxidation. If the semiconductor layer stack 10 is a 25 III/V semiconductor material system based on GaAs, then the oxidizable auxiliary layer 75 and the current aperture layer 60 have a correspondingly high aluminum content, for example, since the proportion of aluminum critically determines the oxidation rate in gallium arsenide layers.

30 The oxidized region of the oxidizable auxiliary layer 75 and the oxidized region of the current aperture layer 60 are indicated by hatching in Figure 2. It can be seen that oxidation is effected significantly "deeper" into the oxidizable auxiliary layer 75 and 35 into the oxidized region of the current aperture layer 60 than into the remaining layers 50, 70 and 80 of the mesa structure 110.

A current aperture 60' of the laser forms in the current aperture layer 60 as a result of the oxidation; the position of a semiconductor relief of the laser is defined in the oxidizable auxiliary layer 75 as a result of the oxidation - as will become clear below. An automatic "self-scaling" thus takes place with regard to the position of the current aperture 60' and the position of the semiconductor relief, since the current aperture 60' and the semiconductor relief are defined during the same production step.

In a subsequent step, a further (second) mask layer 120 - preferably a photoresist mask - is applied to the oxidized mesa structure 110 and also to the (first) mask layer 100 and patterned. The resulting structure is shown in Figure 3.

The resulting structure is subsequently subjected to an etching step which cuts through both the first mask layer 100 and through the covering layer 80. The etching step is ended on the oxidizable auxiliary layer 75. The etching step is preferably carried out as a "selective" etching step, so that the etching of the covering layer 80 is ended automatically.

Afterward, the oxidized region - that is to say the hatched region in Figure 3 - of the oxidizable auxiliary layer 75 is removed selectively. The structure illustrated in Figure 4 is formed, in the case of which the semiconductor intermediate layer 70 has been uncovered at those locations at which the oxidizable auxiliary layer 75 had previously been oxidized.

Etching is subsequently effected into the semiconductor intermediate layer 70, so that a raised region, called semiconductor relief 130 hereinafter, is formed in the semiconductor intermediate layer 70. The resulting structure is shown in Figure 5.

5 The step of etching into the semiconductor intermediate layer 70 may be carried out wet-chemically, for example. In order to achieve an automatic etching stop in the semiconductor intermediate layer 70, a highly doped contact layer, for example, may be integrated therein, the etching step stopping automatically on said contact layer. The highly doped contact layer is indicated by dashed lines in Figure 5 and provided with 10 the reference symbol 150.

15 The etching depth in the course of etching the semiconductor intermediate layer 70 is chosen in such a way as to produce a semiconductor relief in the case of which higher modes of the VCSEL laser to be formed are suppressed to a sufficient extent.

20 Afterward, a metal contact layer 155 is deposited, for example by vapor deposition, on the mesa structure 110 using the second mask layer 120. The resulting structure is shown in Figure 6.

25 Afterward, the further mask layer 120 and also the non-oxidized region of the oxidizable auxiliary layer 75 are removed selectively, as a result of which the covering layer 80 that remains on the auxiliary layer 75 and also the metallization present on the further mask layer 120 are lifted off. The semiconductor structure illustrated in Figure 7 with a semiconductor 30 relief 130 in the semiconductor intermediate layer 70 is formed.

35 An annular metal contact 160 is formed by the residual metal contact layer 155 on the semiconductor intermediate layer 70.

A mirror layer or a mirror layer stack 200 is subsequently applied to the mesa structure in accordance with Figure 7. This may be effected in the

context of a "lift-off" method or in the context of a patterning method. The resulting VCSEL laser is shown in Figure 8.

5 Since the annular metal contact 160 makes contact with a semiconductor layer below the mirror layer or the mirror layer stack 200 and is thus situated in the "cavity region" of the laser, the annular metal contact 160 forms a so-called "intra-cavity contact".

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The second electrical contact required for the VCSEL laser may be arranged - provided that the lower mirror layer stack 20 is conductive - for example on the rear side of the substrate 85; as an alternative, the second 15 electrical contact may be provided as an alloying "intra-cavity contact" on the lower weakly doped laser layer 30.

As can be gathered from the explanations above, the 20 area size or the diameter  $D_s$  of the current aperture 60' in the current aperture layer 60 and also the area size or the diameter  $D_h$  of the semiconductor relief 130 in the semiconductor intermediate layer 70 are determined by the oxidation step to which the sidewalls 25 115 of the mesa structure 110 are subjected in accordance with Figure 2. If production fluctuations or production tolerances then occur during the oxidation step, the area size or the diameter  $D_s$  of the current aperture and also the area size or the diameter  $D_h$  of the semiconductor relief 130 will fluctuate. However, 30 since the current aperture 60' and also the semiconductor relief 130 are produced during the same oxidation step, a virtually fixedly predetermined ratio between the area size of the current aperture and the area size of the semiconductor relief 130 will be 35 formed. The ratio  $D_s/D_h$  will thus remain largely constant even in the event of production fluctuations. An effect of "self-scaling" thus occurs.

In addition, a "self-alignment" between the current aperture 60' and the semiconductor relief 130 also results, since the position of the current aperture 60' and the position of the semiconductor relief 130 are 5 defined by the same mask step.

Figures 9 to 16 show a second exemplary embodiment of the invention. The semiconductor layer stack 10 arranged on the substrate 85 can be seen.

10 A first mask 300 - preferably a hard mask - is applied to the semiconductor layer stack 10, the outer edge 310 of which mask will define the mesa structure of the VCSEL laser (cf. Figure 9). There is an annular cutout 15 present in the inner region of the mask 300 - which cutout is identified by the reference symbol 320 and will subsequently define the annular metal contact 160 in accordance with Figure 7.

20 In a second masking step, the annular cutout 320 is covered with a second mask 330 - preferably a photoresist mask - thereby producing the structure illustrated in Figure 10.

25 A mesa structure 110 is subsequently etched into the semiconductor layer stack 10. The diameter of the mesa structure 110 is defined by the outer edge 310 of the first mask 300.

30 Afterward, the sidewalls 115 of the mesa structure 110 are oxidized. The structure shown in Figure 11 is formed, corresponding to the structure in accordance with Figure 2 apart from the configuration of the upper masks 300 and 330.

35 The second mask 330 is subsequently removed to form the structure in accordance with Figure 12.

Figure 13 shows the resulting layer stack after a third mask 340 - preferably a photoresist mask - has been applied. The third mask serves for covering or protecting the sidewalls 115 of the mesa structure 110.

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The resulting structure is subsequently subjected to an etching step which cuts through the covering layer 80. The etching step is ended on the oxidizable auxiliary layer 75. The oxidized region, that is to say the hatched region in Figure 13, of the oxidizable auxiliary layer 75 is subsequently removed selectively. The structure illustrated in Figure 14 is formed, in the case of which the semiconductor intermediate layer 70 has been uncovered at those locations at which the 15 oxidizable auxiliary layer 75 had previously been oxidized.

Etching is subsequently effected into the semiconductor intermediate layer 70, so that the semiconductor relief 20 130 is formed in the semiconductor intermediate layer 70. The resulting structure is shown in Figure 15.

The step of etching into the semiconductor intermediate layer 70 may be carried out wet-chemically, for 25 example. In order to achieve an automatic etching stop in the semiconductor intermediate layer 70, a highly doped contact layer 150, for example, may be integrated therein, the etching step stopping automatically on said contact layer. A metal contact layer 155 is 30 subsequently deposited, for example by vapor deposition, on the mesa structure 110 using the third mask 340. The resulting structure is shown in Figure 16.

35 The first and third masks 300 and 340 and also the non-oxidized region of the oxidizable auxiliary layer 75 are subsequently removed selectively, as a result of which the covering layer 80 that remains on the auxiliary layer 75 and also the metallization present

on the third mask 340 are lifted off. The semiconductor structure already illustrated in Figure 7 with a semiconductor relief 130 in the semiconductor intermediate layer 70 is formed. An annular metal contact 160 is formed by the residual metallization 155 on the highly doped contact layer 150 of the semiconductor intermediate layer 70.

A mirror layer or a mirror layer stack 200 is subsequently applied to the mesa structure in accordance with Figure 7, as has already been explained in connection with Figure 8. The VCSL laser is thus completed.

The second exemplary embodiment of the invention - in the same way as the first exemplary embodiment - affords self-alignment and self-scaling between the current aperture 60' and the semiconductor relief 130 since the position and the size of the current aperture 60' and the position and the size of the semiconductor relief 130 are defined by the same mask step and the same oxidation step. Moreover, in contrast to the first exemplary embodiment of the invention, the position of the annular metal contact 160 is additionally self-aligned relative to the current aperture 60' and to the semiconductor relief 130 since the position of the annular metal contact 160 is determined by the first mask 300, which also simultaneously defines the position of the mesa structure. Three components, namely the metal contact 160, the current aperture 60' and the semiconductor relief 130 are thus self-aligned.

A third exemplary embodiment of the invention is explained below in connection with Figures 17 to 23.

35

First of all, an annular metal contact 160 is vapor-deposited onto a semiconductor layer stack 450, for example by means of a lift-off method. The semiconductor layer stack 450 corresponds - apart from

the missing oxidizable auxiliary layer 75 and the missing covering layer 80 - to the semiconductor layer stack 10 in accordance with Figure 1 (cf. Figure 17).

5 A first mask 500 - preferably a hard mask made of oxide or made of nitride, for example - is subsequently applied. The first mask 500 has an annular cutout 505, the inner region of which will define a semiconductor relief 130 (cf. Figure 18).

10

An etching step is subsequently carried out, which forms the semiconductor relief 130 below the central region of the mask 500 (cf. Figure 19).

15 A second mask 510 - preferably a photoresist mask - is subsequently applied in such a way that the annular cutout 505 of the first mask 500 is covered. The mesa structure 110 of the laser is then produced by means of an etching step (cf. Figure 20).

20

Afterward, the second mask 510 is removed and the mesa structure is oxidized. The semiconductor relief 130 is thus completed in a self-aligned manner with respect to the current aperture 60' (cf. Figure 21).

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The first mask 500 is also removed in the further course of the process, thereby producing the structure shown in Figure 22.

30 Afterward, on the semiconductor relief 130, an upper mirror layer stack 200 is either applied over the whole area and patterned or produced by means of a lift-off method. The VCSEL laser is thus completed.

35 The third exemplary embodiment affords the self-alignment - already explained in connection with the first exemplary embodiment - between the current aperture 60' and the semiconductor relief 130 since both the position of the mesa structure 110 and thus

the position of the current aperture 60' and the position of the semiconductor relief 130 are defined by the same mask. By contrast, a self-alignment with regard to the annular metal contact 160 does not occur.

5

In the case of the above three exemplary embodiments of the invention, the semiconductor relief 130 is arranged by way of example between the upper mirror layer stack 200 and the current aperture 60'. The area ratio  $D_s/D_h$  10 is by way of example less than 1; this means that the area size ( $D_h$ ) of the semiconductor relief is chosen to be larger than the area size ( $D_s$ ) of the current aperture.

## Reference symbols

- 10 Semiconductor layer stack
- 20 Lower mirror layer stack
- 5 30 Lower weakly doped laser layer
- 40 Active laser layer
- 50 Upper weakly doped laser layer
- 60 Current aperture layer
- 60' Current aperture
- 10 70 Semiconductor intermediate layer
- 75 Oxidizable auxiliary layer
- 80 Covering layer
- 85 Substrate
- 100 Mask layer
- 15 110 Mesa structure
- 115 Sidewalls
- 120 Second mask layer
- 130 Semiconductor relief
- 150 Highly doped contact layer
- 20 155 Metal contact layer
- 160 Annular metal contact
- 200 Mirror layer stack
- 300 First mask
- 310 Outer edge 310
- 25 320 Annular cutout
- 330 Second mask
- 340 Third mask
- 450 Semiconductor layer stack
- 500 First mask
- 30 505 Annular cutout
- 510 Second mask